Hydromorphic change and biotic response challenge efficient river rehabilitation

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From an extensive literature review and meta-analyses, this study has i) identified the most important hydromorphological process related to river degradation and rehabilitation, ii) conceptually linked it to evolutionary and functional response chains of aquatic biota, and iii) provided empirical evidence and ecological data for the respective hydromorphological requirements, preferences and limitations of aquatic plants, benthic invertebrates, lampreys, and freshwater fishes.

Introduction

In Europe the water management recently shifted its paradigm from targeting physical and chemical quality to ecological status and integrity. This includes hydromorphology as a key component of river condition and as the main driving force in rivers. Altered hydromorphology is common in river systems. In the United States 44% of 0.9 million river and stream kilometres have been reported impaired (USEPA 2009). Water diversions, channelization, or dam construction are the second major source of impairment in these rivers behind agricultural use. Habitat alteration occurred in 23.2% of the impaired rivers, and flow alteration in 9.7% (USEPA 2009). In Europe, 64% of 1.17 million river kilometres have been reported to hold less than good ecological status (EEA 2012). Hydromorphological changes and altered habitats have been identified as the most widespread pressure on ecological status of EU waters.

By analysing the first River Basin Management Plans (RBMP), EEA (2012) detected a rather weak linkage between status assessment and the definition and implementation of the measures. Although hydromorphological measures have been systematically included in the RBMPs, only half of the latter indicated specific measures to achieve an ecologically based flow regime and about 40% reported a linkage between water uses, types of hydromorphological pressures and specific hydromorphological measures. Further, it was generally not clear how the proposed measures are expected to contribute to the improvement of the ecological status or potential (Lyche-Solheim et al. 2012). Although, in the past an exponentially increasing number of restoration measures have been implemented to enhance the hydromorphological state of rivers, only very few have been monitored (e.g., Bernhardt et al. 2005, Palmer et al. 2005). The evaluated projects revealed that many measures did not show the desired effects on biota, which might relate to inappropriate scale of measure implementation, confounding impacts of multiple stressors at different spatial scales or insufficient addressing of key elements respectively bottlenecks for target species. In response to the recognized lack of knowledge on the effects of hydromorphological restoration on stream biota, the EU-FP7 project REFORM was drafted building on recent attempts to compile existing data on both, the effects of pressures on hydromorphological processes and variables and the biotic response to hydromorphological degradation and rehabilitation. It has gone beyond recent projects by especially focusing on the specifics of hydromorphology, hydromorphological changes and structures, or features determined by hydromorphology and their linkages to and effects on biota.

Methods

The process-based analysis of impacts relies on understanding systematic relationships between the underlying physical components of hydrology and geomorphology and subsequent biological responses. A bibliographic review has been performed to identify the processes and variables that are associated with the hydromorphological pressures considered. Based on 730 scientific publications reviewed, 15 conceptual schemes have been created showing qualitative interactions between pressures, hydromorphological processes and hydromorphological variables (Garcia de Jalon et al. 2013). Each conceptual scheme was treated as a Fuzzy Cognitive Map (FCM) obtained from scientific literature (according to Özesmi & Özesmi 2004) to identify the most relevant hydromorphological processes and variables. The conceptual schemes link pressures, processes and variables by causal relationships. Responses are visualized by arrows. Arrows received values of -1 for negative relations and +1 for positive. The schemes were then transformed into mathematic adjacency matrices that represent which node of the scheme is adjacent to which other node. All separate matrices (one for each scheme) were then combined into one overall matrix representing a network of all analysed pressures. To combine the schemes, the values of all corresponding arrows were summed up and then normalized by the total number of pressures. Thus, the causal links in the overall matrix are weighted in a continuous range between -1 and +1 according to their importance in the multiple pressure network. As FCMs are based on graph theory models they can be analysed using matrix algebra provided by the graph theory to calculate structural indices. To understand the structure of the system and to identify the most relevant hydromorphological processes and variables the centrality was calculated as a measure of process or variable influence in the network by summing up indegree (cumulative weight of connections entering a variable) and outdegree (cumulative weight of connections exiting a variable). According to Özesmi & Özesmi (2004) the centrality of a variable shows its contribution to the total system, with a high centrality indicating that the variable or process is greatly affecting the system or that the variable or process is being affected by the system.

Assessments of species response and restoration success have to consider ecoregions, biogeographic differences and river types and further require a comparative survey design using reference or control sites respectively before/after samplings. More specific responses or indications have to be expected if certain taxa depend on specific substrates for feeding or spawning and sensitively react on its losses or gains. However, it is inherent in the nature of rivers as disturbance-dominated, dynamic systems that at very fine spatial scales, e.g. at the level of microhabitats, the number of sensitive indicator species is rather low and the uncertainty of assessment and prediction is high. In river systems, coarse gravel requires a significant stream power to be formed and kept clean. Therefore, coarse gravel beds should indicate functioning sediment transport and sorting and thus, hydromorphologically functioning river stretches. Specialized species that essentially depend on well oxygenated permeable gravel beds for spawning or as refuge provide a direct link to high quality gravel beds and thus, serve as biological indicator for the respective hydromorphological processes. In contrast, typical substrates provided by other than gravel-bed rivers are either not exclusively found in rivers and formed by stream power (e.g. large wood) and thus not indicative for hydromorphology, or there are no species specifically responding to it (e.g. bedrock). However, wood, plant beds, large stones and similarly complex structures provide habitat and shelter and as such they mitigate impacts of physical forces like high flow velocities and stream power on aquatic organisms. Especially the distribution of juvenile and small fish, lentic invertebrates and submerged plants becomes restricted by high flow velocities and shear forces. Accordingly, habitat complexity, habitat structures and connectivity enable habitat utilisation by weak swimmers and fragile taxa. Hence, these structures determine functional responses of aquatic taxa in terms of abundance, species density, diversity and carrying capacity.

Accordingly, the review of biological responses to hydromorphological processes and variables primarily focused on gravel requirements and flow preferences of aquatic macrophytes, benthic invertebrates and fish as well as on their performance thresholds and limitations to withstand higher flow velocities, shear forces and stream power.

Hydromorphological processes and variables

The overall hydromorphological pressures and effects system investigated shows a high complexity value (2.6) indicating that the system results in many outcomes and responses in relation to relatively few forcing pressures. Hierarchy was calculated as 0.0002, which corresponds to the relatively high complexity value and shows that the system is not hierarchical structured. The system had a density value of 0.036 indicating relatively complex causal relationships between pressures, variables and processes in the system compared to the total possible number.

The most central process in the network is the water flow dynamics, followed by vegetation encroachment, and sediment entrainment in order of importance. Although it sounds so trivial that water flowing is an important river process, this result of the meta-analysis is highly relevant for river rehabilitation and management. Despite substantial uncertainties about interaction effects of multiple pressures and different scales, this FCM meta-analysis has simultaneously included all reported pressures and processes in a single comprehensive analysis. And the result showed water flow dynamics as the primary driver of ecological change in altered systems. Hence, it is concluded that the rehabilitation of the natural flow regime should get priority in river rehabilitation.

Linkage to biology

Flowing water as most important process drives sediment erosion, deposition, transport and sorting, and by that provides sediments of certain quality and calibre. Species evolutionary adapted to and essentially depending on using these specific substrates are considered as specific indicators or target species for hydromorphological rehabilitation. Examples include primarily the gravel spawning fish species. Gravel spawning is a life history trait that has evolved in high energy rives in response to the available habitats and substrates.

The response of aquatic biota to habitat complexity and diversity in relation to stream power is rather unspecific and of functional nature. Structured habitats provide shelter from high flows and high stream power. However, this shelter function is similarly provided by several different habitats structures such as large wood, macrophytes stands or boulders. It is further important to mention that for the provision of shelter these natural features can be substituted by rehabilitation measures, e.g. artificial structures.
In principle there are to direct links between hydromorphology and biota, first, the environmentally sensitive gravel spawners reflecting an evolutionary process in response to hydromorphological processes; and second, the carrying capacity in terms of abundance, biomass and diversity as functional response to available resources and habitats.

Biotic response

The review revealed an overall limited autecological knowledge on the life history traits of European freshwater species and accordingly, yielded a rather limited set of specific indicator species that directly respond to hydromorphological integrity in terms of habitat dependence.

Of about 500 macrophytes species, 20,000 freshwater benthic invertebrates species and 550 lamprey and fish species known from Europe, ecological information is published for 176 species, 1118 taxa, 218 species, respectively, including 75, 78, and 218 species, respectively, with reported flow preferences, and 10, 56, and 28 species, respectively, with reported gravel calibre information (Fig. 1, Wolter et al. 2013). However, the relation of autecologically described species and species preferring coarse substrates clearly indicates, that the latter are primarily relevant for fish, while benthic invertebrates and plants rather respond to the physico-chemistry of the water.

The unspecific, functional response to hydromorphology is determined by tolerance thresholds of species, age groups and life stages against high flow velocities and shear stresses, which restrict habitat use up to the complete disappearance of species. Common thresholds values of flow velocities reported were <0.3 m/s for species-rich, diverse macrophyte communities (Janauer et al. 2010), 0.3-1.0 m/s for rheophilic invertebrates (Statzner et al. 1988, Söhngen et al. 2008), and 0.1 m/s and 0.5 m/s for hatchlings and juvenile fish, respectively (Wolter & Arlinghaus 2003).

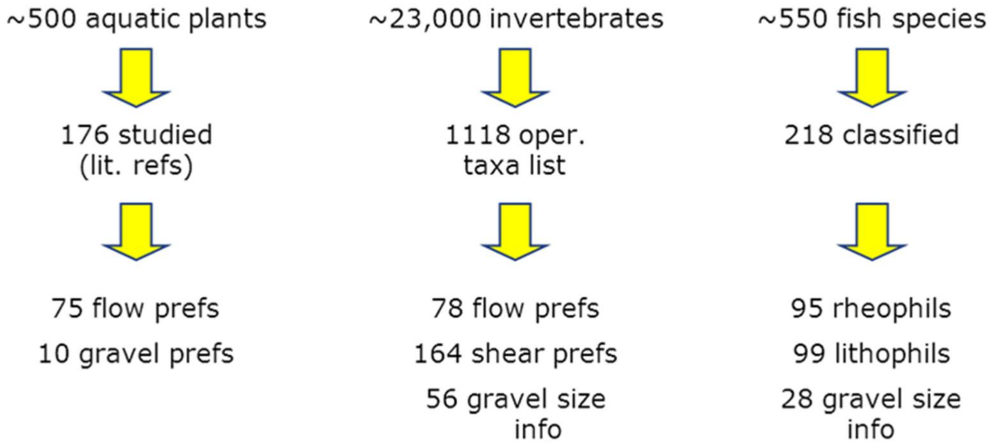

Fig. 1 Summary (number of species) of the reported ecological information for the three studied taxonomic groups.

The functional response is further reflected in the carrying capacity of a river stretch, where diverse and complex habitats support higher densities, e.g. of juvenile fish. In a braided river stretch emerging fish fry was predicted to settle ten times faster in suitable nurseries compared to a regulated single thread reach (Sukhodolov et al. 2009).

In principle, more indicators (species traits, population metrics, juvenile fish, and aquatic plants) are available for the functional response to habitat complexity and diversity, whilst the evolutionary response to coarse gravel substrates as result of hydromorphological processes is mainly expressed by lithophilic fish (Wolter et al. 2013). Benthic invertebrates were found intermediate responding with significant influence of water quality (Wolter et al. 2013).

Conclusions

Among all simultaneously interacting pressures and processes flowing water has been identified as the most relevant. Accordingly, river rehabilitation should primarily focus on rehabilitating natural flow dynamics and related processes. The biotic response to hydromorphological changes, degradation and rehabilitation is mainly related to habitat complexity and coarse substrates. The functional response was found most pronounced for aquatic plants, juvenile fish, and the fish assemblage as a whole; while a specific response was especially obvious for lithophilic fish. Accordingly, the responding taxa, age groups and life history traits identified should also serve as rehabilitation targets.

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